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Electrically-generated spin polarization in non-magnetic semiconductors

Vanessa Sih
UNIVERSITY OF MICHIGAN

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Final Report

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14. ABSTRACT

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Final Performance Report for “(YIP) – Electrically-generated spin polarization in non-magnetic semiconductors” (Contract/Grant Number: FA9550-12-1-0258)

Author: Vanessa Sih

Date: March 14, 2016

Abstract

The objective of the research was to investigate and determine the mechanism that produced electrically-generated electron spin polarization in non-magnetic semiconductor heterostructures. Electrically-contacted indium gallium arsenide samples were fabricated and measured using time- and spatially-resolved magneto-optical measurements. Measurements of electron spin dynamics as a function of pump-probe spatial overlap and applied electric and magnetic fields were used to characterize the momentum-dependent spin-orbit fields. The electrically-generated electron spin polarization was shown to be inversely proportional to the measured momentum-dependent spin splitting in strained indium gallium arsenide, contrary to theoretical expectation. The measurements were conducted by systematically varying the direction and magnitude of the in-plane current and net drift momentum in a device with a cross-bar geometry and by varying the direction of the applied magnetic field with a rotatable cryostat. The role of electrically-generated electron spin polarization in producing dynamic nuclear polarization was investigated, and nuclear spin polarization was produced that could be aligned either with or against the applied magnetic field, depending on the direction of the current. A phase shift in the time-resolved Faraday rotation data due to electron spin polarization from previous pump pulses was characterized, and an analytic solution for this phase shift was found. The electron g-factor was also shown to change with increasing in-plane electric field due to increasing electron temperature. A series of indium gallium arsenide epilayer samples with varying indium composition and doping density were produced and measured in order to determine how changing the sample parameters, such as spin-orbit splitting, spin relaxation time, momentum scattering time, and carrier density, affect the electrical spin generation efficiency.

Summary of Work Accomplished

The goal of this project was to enable the design of materials with large, robust electrically-generated electron spin polarization by experimentally determining how key material parameters, such as spin-orbit splitting, spin decoherence rates, momentum scattering time, and carrier density, govern the magnitude of electrically-generated spin polarization in semiconductors.

Custom indium gallium arsenide (InGaAs) heterostructures were supplied by the research groups of Prof. David Awschalom at the University of California at Santa Barbara (currently at U. Chicago) and Prof. Rachel Goldman at the University of Michigan. Electrically-contacted devices for the experiments were fabricated using photolithography, chemical etching, metallization, and thermal annealing at the Lurie Nanofabrication Facility at Michigan.

Time- and spatially-resolved magneto-optical spectroscopy were conducted to measure the electron spin decoherence time, map the momentum-dependent spin-orbit fields, and determine the magnitude of current-induced spin polarization. A cross-bar-shaped device with four

electrical contacts was designed and fabricated so that the direction of the in-plane electric field could be varied. A rotatable cryostat mount was used so that the direction of the applied magnetic field could be controlled relative to the sample axes.

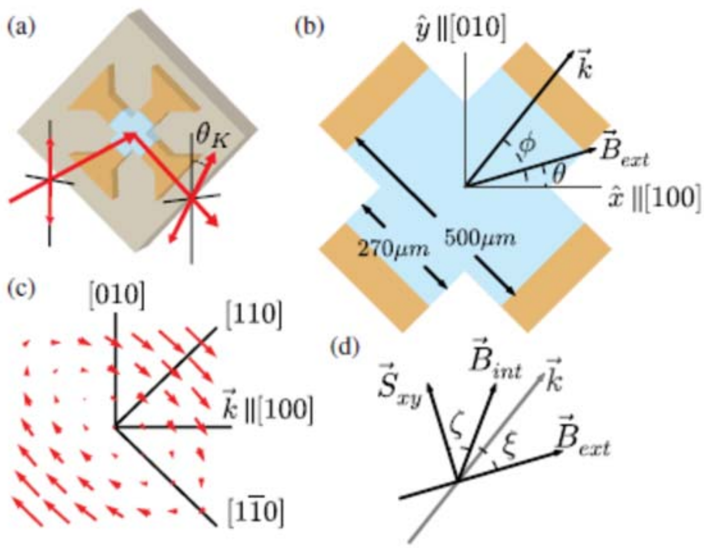

Figure 1. (a) The InGaAs epilayer (blue) is etched into a cross pattern with four electrical contacts (orange). Kerr rotation measures the component of spin polarization along the laser axis. (b) Voltages applied to the contacts determine the electron drift momentum $\vec{k}$, at angle ϕ with respect to the [100] crystal direction. $\overrightarrow{B_{ext}}$ is oriented at angle θ by rotating the cryostat. (c) Total spin-orbit field as a function of $\vec{k}$ if the Rashba field is twice as large as the linear Dresselhaus field. (d) The spin-orbit field $\overrightarrow{B_{int}}$ makes an angle with respect to $\overrightarrow{B_{ext}}$ and the steady-state in-plane spin polarization. Reproduced from [2].

These measurements and phenomenological modeling established that spins are dynamically polarized along the direction of the spin-orbit field, but the steady-state electrically-generated spin polarization can deviate from this direction due to anisotropic spin relaxation. Contrary to existing theories, the measurements also show that the electric field directions corresponding to the smaller spin-orbit splitting produce the larger electrical spin generation efficiency [2]. Detailed descriptions of the optical techniques and modeling are published in Ref. [D1].

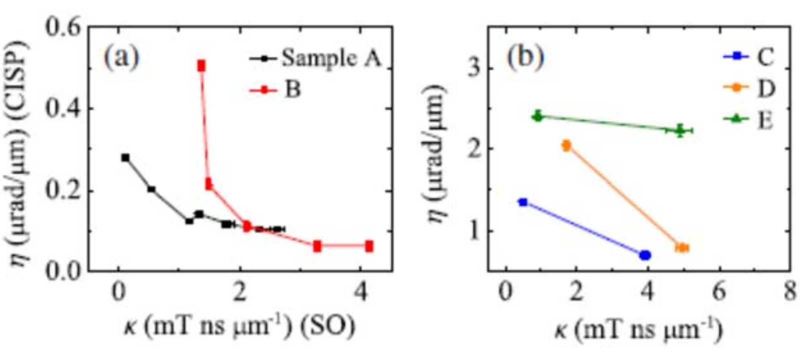

Figure 2. Electrical spin generation efficiency for each direction of in-plane electric field plotted against the spin-orbit splitting for the same direction for (a) two cross-bar devices and (b) three fixed-channel devices. Reproduced from [2].

Current-induced electron spin polarization was shown to produce nuclear hyperpolarization through dynamic nuclear polarization. Time-resolved Faraday rotation measurements were used to monitor the total effective magnetic field produced by the sum of the applied magnetic field, spin-orbit field, and nuclear (Overhauser) field as a function of laboratory time and applied electric field. The nuclear field saturated over a timescale of 100 s and was shown to depend on the direction of the current-induced electron spin polarization relative to the applied magnetic field. The dependence of the saturated magnetic field as a function of temperature, electric field strength and external magnetic field strength was measured [3].

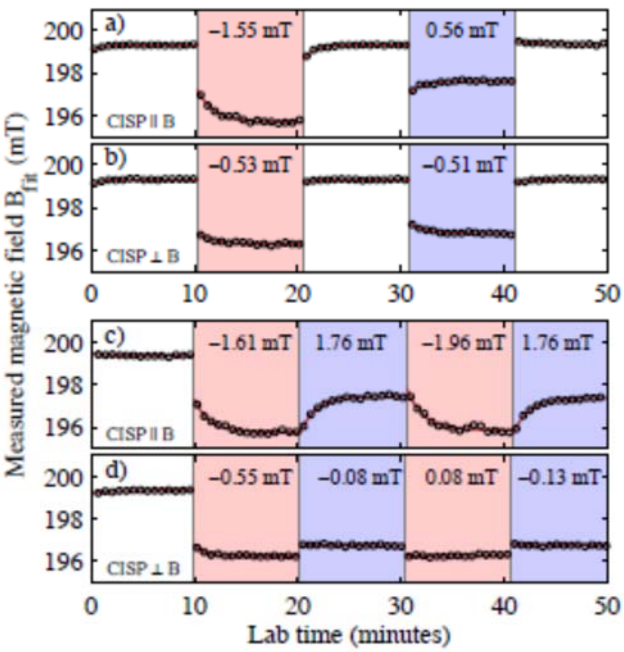

Figure 3. Total magnetic field measured using time-resolved Faraday rotation with the electrically-generated electron spin polarization parallel [panels (a) and (c)] and perpendicular [panels (b) and (d)] to the applied magnetic field. All data were measured at 10 K with B = 200 mT. Light red and light blue shading indicate V_{DC} = 2 V and -2 V, respectively. Inset text gives the total change in nuclear field for the labelled transition. Panels (a) and (b) show transitions of the form V_{DC} = 0 to ±2 V, which include contributions from effects that depend on current magnitude, such as the changing spatial overlap of the optically-induced spin polarization with the region of interest and electrical heating. Panels (c) and (d) show transitions of the form V_{DC} = -2 V to 2 V, which only includes effects due to the change in current polarity. Reproduced from [D2].

In the course of performing time-resolved Faraday rotation measurements as a function of applied magnetic field, a phase shift in the time-resolved Faraday rotation data was identified, and an analytic solution for this phase shift as a function of spin lifetime was found [5]. Detailed descriptions of the measurement techniques and modeling are published in Ref. [D2].

A closer analysis of the time- and spatially-resolved Faraday rotation measurements used to measure the magnitude and direction of the spin-orbit fields found that the measured electron g-factor also exhibits a dependence on applied electric field, which can be attributed to the increased electron temperature [8].

A series of indium gallium arsenide epilayer samples with varying indium composition and doping density were produced and measured in order to determine how changing the sample parameters, such as spin-orbit splitting, spin relaxation time, momentum scattering time, and carrier density, affect the electrical spin generation efficiency.

Graduate students involved in this project

Benjamin M. Norman
Christopher J. Trowbridge
Marta Luengo-Kovac
Michael Macmahon
Eunice Paik

Dissertations produced

[D1] "Electrical Generation of Spin Polarization in Strained III-V Semiconductors," Benjamin Michael Norman, Ph.D. thesis, University of Michigan, Ann Arbor (2014), available online: http://hdl.handle.net/2027.42/108822

[D2] "Electron and Nuclear Spin Dynamics and Coupling in InGaAs," Christopher J. Trowbridge, Ph.D. thesis, University of Michigan, Ann Arbor (2015), available online: http://hdl.handle.net/2027.42/113488

Publications in peer-reviewed journals

[1] "Spin lifetime measurements in GaAsBi thin films," B. Pursley, M. Luengo-Kovac, G. Vardar, R. S. Goldman, and V. Sih, Applied Physics Letters **102**, 022420 (2013).

[2] "Current-induced spin polarization in anisotropic spin-orbit fields," B. M. Norman, C. J. Trowbridge, D. D. Awschalom, and V. Sih, Physical Review Letters **112**, 056601 (2014). Selected as an Editors' Suggestion.

[3] "Dynamic nuclear polarization from current induced spin polarization," C. J. Trowbridge, B. M. Norman, Y. K. Kato, D. D. Awschalom, and V. Sih, Physical Review B **90**, 085122 (2014)

[4] "Anisotropic spin dephasing of impurity-bound electron spins in ZnO," J. Lee, A. Venugopal, and V. Sih, Applied Physics Letters **106**, 012403 (2015)

[5] "Phase effects due to previous pulses in time-resolved Faraday rotation measurements," C. J. Trowbridge and V. Sih, Journal of Applied Physics **117**, 063906 (2015)

[6] "Robustness of n-GaAs carrier spin properties to 5 MeV proton irradiation," B. C. Pursley, X. Song, R. O. Torres-Isea, E. A. Bokari, A. Kayani, and V. Sih, Applied Physics Letters **106**, 072403 (2015)

[7] "Amplifying optical rotation using a coupled waveguide and ring resonator," T. W. Saucer, C. Zerger, B. Pursley, and V. Sih, Optics Express **23**, 6050-6057 (2015)

[8] "g-factor modification in a bulk InGaAs epilayer by an in-plane electric field," M. Luengo-Kovac, M. Macmahon, S. Huang, R. S. Goldman, and V. Sih, Physical Review B **91**, 201110(R) (2015)

[9] "Resonant and time-resolved spin noise spectroscopy," Brennan C. Pursley, X. Song, and V. Sih, Applied Physics Letters **107**, 182102 (2015)

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[9] "Resonant and time-resolved spin noise spectroscopy," Brennan C. Pursley, X. Song, and V. Sih, Applied Physics Letters 107, 182102 (2015)

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